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Technological advances and applications of geothermal energy pile foundations and their feasibility in Australia

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ABSTRACT

Geothermal energy pile foundations are an alternative energy source for heating and cooling needs. Utilising this source of energy has great potential due to the environmental, economic and social benefits. This paper looks at an extensive amount of literature on the technology behind the system including the overall process, primary considerations for each of the main components including latest developments as well as design implications such as the integration of ground energy systems into structural piles of buildings. Environmental considerations including performance-dependent parameters of the subsurface are described. Main parameters include thermal conductivity, thermal diffusivity, specific heat capacity and moisture content. Temperature and groundwater effects are also discussed and design considerations are provided. Mathematical models are available to aid in the design of these systems but there are various other issues and complex parameters that need to be considered qualitatively. Furthermore, the design of these systems is governed by various standards and government legislation. Case studies are presented to show the application of these systems in practise including assessments of system performance. Examples originate from countries such as Austria, Switzerland, Germany, UK, USA, Japan, Iran, Sweden and Norway. Benefits and limitations of implementing these systems are summarised and finally, the feasibility of geothermal energy pile foundations in Australia is explored. This paper found that these systems, although exhibiting some limitations and possible challenges, are a viable option in terms of an alternative energy source.

Contents

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1. Introduction

The issue of climate change is one of the greatest economic, social, and environmental challenges that the world has been exposed to. The way humans behave today is affecting what the world will be like tomorrow. Countries, governments and individuals need to find ways of reducing the carbon footprint and one such option is the utilisation of alternative, renewable energy sources.

To help encourage, educate and lead people in the right direction, legislations across the globe, internationally recognised and locally introduced, are being passed through governments to ensure that carbon reductions can be achieved in the near future. Examples of such procedures are the Kyoto protocol, the Climate Change Act 2008 in the UK [1] and numerous Australian policies such as the *Target 2020*, the *green paper* and the *white paper*. Australian legislations include alternative energy sources as a key tool in reducing carbon emissions and have specific targets such as the Mandatory Renewable Energy Target (MRET) [2,3]. With new technologies in the field of the alternative energy sources being continually developed and the recognition of its important contribution earned by government organizations and the general public, implementation has recently become more feasible.

Traditional geothermal energy systems require interaction with kilometre-deep strata of rock, where thermal energy is much greater and can produce hot fluids to drive turbines for electricity [4]. Its use is however weighed down by cost and practicality, a technology that is more suited for larger scale applications. More recently, encouraging developments are being achieved in the field of shallow geothermal energy systems. These systems show great potential, comparative to the traditional systems, in terms of long-term sustainability, access, flexibility and economics. Shallow geothermal energy is based on the principle that the subsoil can be employed as a thermal energy source by using its natural potential and thermal storage capabilities [5]. The use of these systems is however limited to heating applications due to the lower temperatures extracted. The benefits of this environmentally sustainable technology nevertheless make it an attractive alternative to conventional heating systems, which require larger amounts of input energy and thus leads to increased greenhouse gas production.

Ground-source heat pump systems are a technology that taps into the shallow ground as a geothermal energy source. A subset of this system (and the focus of this paper) involves geothermal energy piles, also termed closed-loop systems [6]. The most common application of these systems has been to achieve energy-efficient space heating and cooling for both residential and commercial buildings of various sizes while satisfying load bearing requirements of the underlying foundation [7].

Various statistics highlight the increase in popularity of this sustainable technology. A total of 80 countries (as of 2000) have used some form of geothermal energy [8]. Yari and Javani [9] indicate that installations of shallow energy systems have increased from 26 countries in 2000 to 33 in 2007. The number of installations worldwide at present can be said to have reached the one million mark as indicated by several authors [10,11]. It is evident that with further development of this technology, increased applications in both quantity and diversity will be seen in the next few decades.

The following review will provide insight into many aspects of this young technology. Technical background and environmental considerations will assist in understanding the various factors that govern the design of these systems. Experience and a wide range of applications that have been documented in past decades will be provided. Evaluation will feature environmental, social and economical aspects of energy piles, highlighting various benefits and limitations that their implementation may hold. The aim of this review is to ultimately determine future prospects of this technology, highlight areas that need further research as well as provide a feasibility assessment of this technology for the Australian environment.

2. Technological background

This section will give an overview of the main system and its sub-components. Various design implications conclude this section.

2.1. Process of the overall system

The conventional description used by many [12,13] has involved dividing up the overall system, shown in Fig. 1, into three major components:

- the primary unit (ground heat exchanger),
- the heat pump and
- the secondary unit (pipework for heating of the receiving infrastructure)

Preene and Powrie [4] have recently proposed an alternative categorisation of the system into three main components: 'the source side', 'the load side' and 'the heat transfer system'. As will become apparent, this second classification represents a more

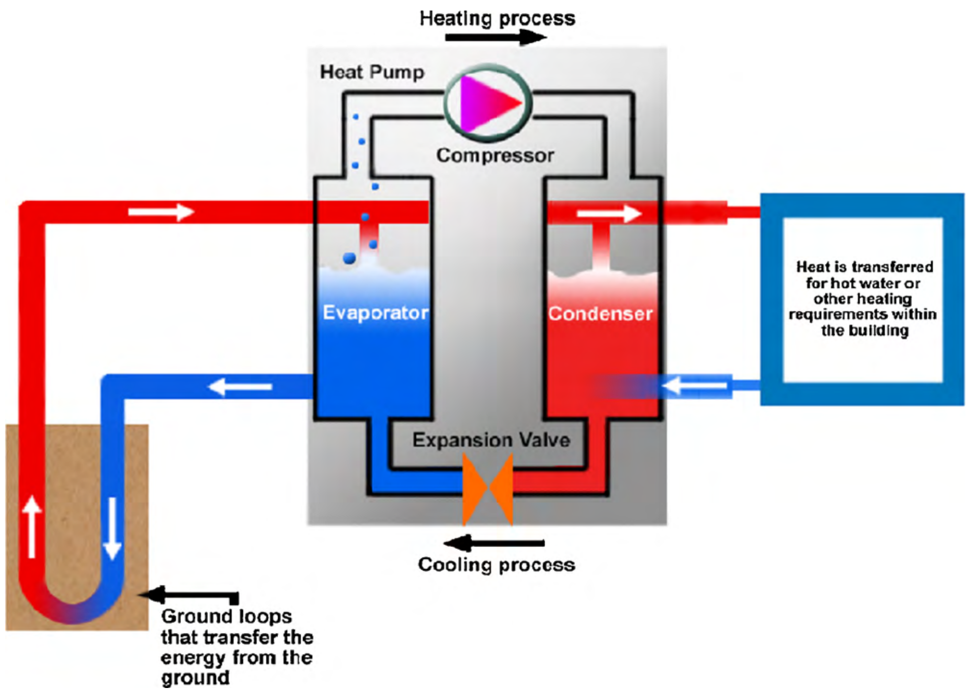

Fig. 1. Process of the overall system heating only.Adapted from [14] and [15].

function-based characterisation as compared to a component-based approach conventionally adopted. The roles of some components will change when considering the use of these systems in heating and cooling modes. Ground-source heat pumps can be designed to operate as a single mode system only or can incorporate both heating and cooling operations.

Ground heat exchangers constitute the primary unit of the overall system with the task of extracting and injecting heat into surrounding soil. Conduction and convection are the two primary heat transfer mechanisms that take place between soils surrounding these subsurface elements as heat absorbing fluid is circulated through a loop of pipes embedded within these exchangers [4,11,13]. A pump is responsible for driving the flow of heat transfer fluid through the subsurface pipes. For heating operations, the thermal energy obtained from the ground is transferred to the heat pump, which uses a compressor (reverse refrigeration method shown in Fig. 1) to elevate temperatures, the resulting thermal gradient from which is subsequently used to heat fluid or air within the secondary unit [14,16]. During cooling mode, the surrounding environment transmits heat to the secondary unit (connected to the primary unit through the heat pump) and the reverse heat pump cycle conveys this thermal energy into the ground. Heat is transmitted from the secondary unit to receiving infrastructure in heating mode and vice versa in cooling mode. Each unit undergoes the constant heating-cooling or reverse cycle driven by the help of the heat pump.

It is important to note that these systems do not completely offset the energy usage and that electrical energy input is still required to drive the heat pump. To quantify the temperatures, which need to be achieved by the pump, an example by Brandl [12] suggests that initial temperatures of 10–15 °C that can be obtained from these shallow geothermal systems need to be elevated to a temperature range between 25 and 35 °C.

Systems can operate both heating and cooling functions seasonally. In summer, the ground is used as a heat sink where thermal energy is stored in an effort to cool the infrastructure. This heat is extracted in winter for heating purposes as the ground changes its role to a heat source [17,18]. Primary and secondary units therefore reverse roles during different seasons between 'source side' and 'load side', explaining the function-based definition of components by Preene and Powrie [4]. In the event of an imbalance in heating and cooling loads, additional efforts can be made to reduce long-term temperature changes as discussed in Sections 5.2 and 5.3. Potential environmental issues associated with thermal imbalances are discussed in Section 3.

2.2. Types of ground-source heat pump systems

Ground-source heat pumps primarily consist of two types: Open- and closed-loop systems. Open systems directly utilise the ground's thermal storage medium. Groundwater is pumped from a well to the heating system to provide thermal energy to the secondary unit with the help of the heat pump. After the heating operation, water (at a significantly different temperature) is either injected back into the aquifer (using a second well) or disposed off in surface water bodies [4,19,20]. Although these systems have been widely used and involve lower initial costs, long-term high financial, technical and environmental risks have become apparent [21,22]. Further limitations are restrictive regulations on groundwater use, required water quality (low iron content), limited availability of installation sites and required aquifer size. All these factors have caused a shift in preference to closed-loop systems [20,21].

Closed-loop systems adopt a method whereby the heat transfer process occurs indirectly between soil and a heat carrier medium flowing through pipes. Energy piles are a form of closed-loop system, however alternative configurations exist using loops of pipes (without foundation elements or embedded in other structures such as diaphragm walls) placed horizontally (easier construction) or vertically (preferred configuration) beneath the ground [11,19,20,23]. Vertical systems are generally preferred due to their lower surface area requirements, shorter pipe lengths, lower pumping costs and higher efficiency with less variability. Horizontal loops are affected by shallow ground temperature fluctuations (more details provided in Section 3) [24]. Closed-loop systems are regarded to have a higher initial cost in comparison to open systems, but this is offset by greater versatility, long-term economic benefits and lower long-term risks permitting their installation under many types of ground conditions.

2.3. Energy pile materials

Geothermal energy piles fulfil two purposes, they are designed as both structural foundation elements and ground heat extraction. As Boennec [22] states, one drilling operation is only required to achieve two objectives suggesting significant savings on installation costs. These two purposes need to be considered during the design step of material allocation.

The main materials used in the construction of bearing or friction piles that have been used in past geothermal energy pile studies [7,14,25,26], include the following:

- Precast or cast in situ reinforced concrete
- Steel, and
- Grout

Reinforced concrete piles have been found to be advantageous due to the material's high thermal storage capacity and enhanced heat transfer capabilities [7,14]. In fact, concrete energy piles represent the majority used around the world [12]. Precast or driven piles are less favoured in comparison to the more subtle technique of cast in situ piles (common method is rotary bored) as the latter technique poses less harm to the integrated heat exchanger system.

Steel piles were of interest during the initial stages of energy pile research and have not earned as much appreciation by researchers as concrete piles. A study by Morino and Oka [25] however featured tests performed on these piles employing the use of a 20 m deep vertical installation with solar collectors used for heating and a refrigerator used for cooling. It was at the time thought that steel should greatly assist in the heat transfer between ground and circulating fluid due to its low thermal resistance and high thermal conductivity [26]. Nagano [26] suggested that there were two possible ways of incorporating ground heat exchange by use of a steel pile: direct water circulation (open system) or the more preferred option of using heat carrier pipes (indirect, closed-loop system).

Variations of the above pile designs are described by Brandl [12] and include steel tube piles filled with concrete and heat exchangers as well as vibrated concrete columns outfitted with heat absorber pipes installed using the vibroflotation technique. Partially grouted stone columns have also been used, but have lower geothermal efficiency [12]. This is primarily due to the grout, which has been an issue with other ground-source heat exchanger systems in particular, borehole heat exchangers [27–30]. Grout, however is an important component for borehole heat exchangers as it supports the pipes and protects groundwater from contamination as a result of pipe leaks [21]. Consequently, specific measures need to be met to ensure successful thermal performance. Measures suggested by Esen and Inalli [30] include the reduction in grout volumes required or the use of clips to hold pipes against borehole walls.

The use of thermally enhanced bentonite grout or mixtures with sand will overcome issues of low thermal conductivity experienced with standard grout [28–30]. It is known that increasing quartz content will improve thermal conductivity of the soil [31]. In addition to these suggestions, it must also be ensured that the grout will maintain its thermal properties throughout the pile's operation [27]. Enhancing the geothermal efficiency of grouted energy columns can therefore be achieved and may potentially reduce the overall cost of the system by minimizing overdesign of the foundation (especially when piles are not required for bearing support). The choice of alternative heat exchanger systems may however be preferable from an economic and practical standpoint in such cases.

2.4. Absorber pipe materials, shape and heat carrier fluid

Absorber pipes are commonly made of high-density polyethylene (HDPE), but PVC has also been trialled in the past [7,18,25]. For concrete piles, the pipes are fixed to the reinforcement cage. Prior to placement of concrete, pipes are pressurised. This pressure is maintained to resist the external wall pressures imposed by the wet concrete and relieved only once the concrete has hardened after a few days [12]. Pipe diameters range from 20 to 25 mm and their lengths will depend on several factors including pile length and performance requirements.

Heat transfer liquid, which is fed through the pipes serve the purpose of transmitting or receiving heat to and from the ground. For buildings where the cooling loads are much greater than heating loads, water may be sufficient [6]. Its use is common, but not recommended in colder climates, where freezing of the fluid can occur resulting in damage to the pipes. For cooler climates, antifreeze solutions such as water and glycol mixtures, saline solutions, brine, potassium acetate or even methanol are possible substitutes [12,14,18,32,33]. Ozgener and Hepbasli [33] for example prepared a 10% ethylene glycol mixture by weight to serve as the heat carrier medium.

The installed pipes adopt the form of continuous loops of certain shapes. The choice of shape will affect the overall efficiency of the system. Common shapes, shown in Fig. 2, featured in several studies (see [7,23,34]) are:

- Single, double and triple U-shaped pipes
- W-shaped pipes

Single or multiple U-shaped or W-shaped pipes are the main types installed within the concrete piles. Single U-shaped pipes were featured in Florides and Kalogirou [23] and Hamada et al. [35] and were regarded as the most efficient choice from an economic standpoint and in terms of workability [35]. Experimental testing and numerical simulation results reported by Gao et al. [7,34] concluded that W-shaped loops were more effective than U-shaped loops, but its performance offset by high cost.

2.5. Heat pump

The heat pump is a mechanical device that functions like a reverse refrigerator. Its basic components include the compressor and expansion valve. The former compresses the refrigerant within the pump to a gaseous state of elevated temperature and pressure. In passing through the pump towards the expansion valve, heat is exchanged with the secondary unit leading to a decrease in temperature of the refrigerant. Upon reaching the expansion valve, the gas undergoes a change of state from gaseous to liquid and the cycle repeats itself. Primary and secondary units will supply and receive the thermal energy contained within the pump allowing for the cycle to run. Reversible heat pumps are required for

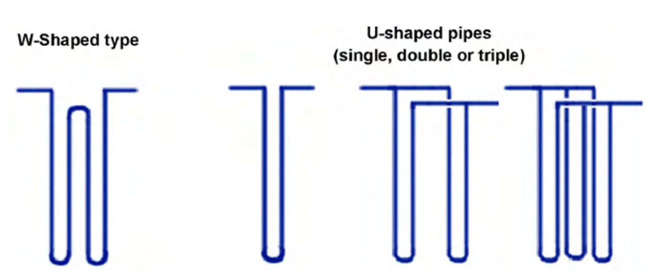

Fig. 2. Four types of pipe configurations for energy piles.Adapted from [34].

seasonal operation of the ground-source heat exchanger system as winter and summer cycles require different heating and cooling operations to take place [12,14].

This component is regarded as the most energetic of the entire system [28,29]. Careful design must ensure that the efficiency of the pump does not greatly affect the performance of the entire system. Details of its selection will be presented in Section 4. For systems, which are designed solely for the purpose of cooling, efficiency can be increased and energy saved by following the recommendation of omitting the pump and instead using plates for heat exchange [4]. Little is however known about the performance of this modification.

2.6. Secondary unit

The secondary unit consists of pipes embedded in floors and walls of buildings, bridges, beneath roads and other infrastructure, which require heating. Its primary function is to utilise the extracted thermal energy for heating purposes during the winter and to receive unwanted heat from its surroundings in summer for transfer into the ground.

3. Environmental considerations

Heat transfer between the geothermal energy systems and their surrounding environment (of soil and rock) involves a very complex collection of processes, which require a thorough understanding if efficient design is to be achieved. In practice, the system is likely to penetrate several geologic strata each exhibiting different thermal properties and geothermal potential. The ability of a vertical ground heat exchanger to operate with the ground depends on local geology, hydrogeology and other conditions that impact the feasibility and economics of the system. Furthermore, the ground temperature distribution, soil moisture content and its influence on thermal properties, groundwater movement and possible freezing and thawing in soil affect performance of the system [36]. As a result, understanding the relevant, complex ground thermal properties and behaviour, site history, climate conditions, groundwater effects, spatial and temporal variations is paramount. These issues are covered in this section.

3.1. Heat transfer processes

Hepbasli et al. [28,29] explain that the operation of the heat exchanger induces simultaneous heat and moisture flow in the surrounding soil. The transfer of heat is primarily due to heat conduction and to a certain degree by moisture migration. This indicates that the efficiency of the heat transfer processes is strongly dependent on soil type, temperature and moisture gradients. Rees et al. [37] explain that the transport of heat in porous media may be induced by several mechanisms: conduction, convection and the transfer of heat due to water phase changes, also known as latent heat of vaporisation. Radiation is generally assumed to be negligible. Brandl [12] confirms these relevant processes and adds to this list by including condensation, ion exchange and freezing–thawing cycles.

Several studies agree that, under normal circumstances, conduction is the most significant process to consider [9,12,37,38]. Heat conduction is the process whereby heat is transferred from one region of the medium to another, without visible motion [37]. The heat energy is passed from molecule to molecule and Thomas and Rees [38] explain that heat conduction is mainly dependent on the degree of saturation of the soil. Clarke et al. [11] report that thermal conductivity and specific heat capacity of the soil mass are also influential factors.

Heat convection (though not as dominant as conduction, but important) is the process where heat is transported in a fluid by means of circulation flows [37]. Therefore, particle movement exclusively induces convection effects. These are only an issue with fluids and vapour that may be present, since the subsurface is generally considered as static. This may play a role in granular soils since the hydraulic conductivity is large enough to allow water to flow through the soil at relatively fast rates compared to fine-grained soils [11]. The two further minor heat transfer processes, which should nevertheless be considered, are the latent heat of vaporisation and freezing–thawing cycles. The former becomes an issue when taking into account heat transfer caused by the transport of vapour in the medium and arises due to phase change. The process is usually only significant when dry conditions exist [37]. Although the latter process can transfer significant heat, freezing–thawing behaviour should be avoided for ground-source heat exchangers [12].

Brandl [12] explains that all these processes mentioned can be considered theoretically in terms of heat exchange between fluid, concrete and soil but is limited to steady state flow and heat transfer problems. The importance of distinguishing between the existences of laminar and turbulent flow within the system needs to be considered as they each will result in different heat transfer rates and consequently affect the overall performance of the system. Laminar flow can generally be determined theoretically, turbulent flow conversely requires detailed experimental data to be obtained.

3.2. The impact of ground temperature and specific temperature regimes

This system aims at utilising the subsurface of the Earth as it contains an enormous potential of stable geothermal energy. The two main considerations for the use of goethermal energy is the need of a widely constant temperature of the ground [13] and the magnitude of ground temperature. The latter as it affects the thermal gradient between environment and system, which drives the heat transfer [21].

Temperature variability below ground is highly dependent on depth due to the heat capacity of the soil. This relationship is shown in Fig. 3 for various sites in Victoria. It has been well established that the range of seasonal variation in ground temperature decreases with increasing depth below the ground surface [20,23,38–40]. In addition to this, Preene and Powrie [4] report that at sufficient depths, where stable ground thermal behaviour is achieved, soil temperature in summer months will be cooler than that of the surface air allowing heat to be rejected to the ground. Conversely, in winter the soil below ground will be warmer than surface air temperatures and can be used as a heat source. Popiel et al. [41] and Wang and Qi [40]

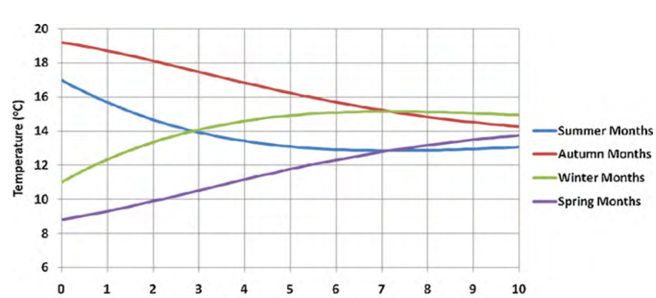

Fig. 3. Measured temperature variation vs. depth below surface relationship during different seasons for typical Australian ground.

describe the temperature–depth relationship using three main ground zones:

- *Surface zone*: Significant fluctuations in temperatures occur due to short-term ambient variations, spanning to depths of approximately up to 3–5 m below the surface.
- *Shallow zone*: Temperatures are less sensitive, but still influenced by seasonal changes throughout the year, ranges in depths highly dependent on soil type and saturation levels between approximately 1 m and 20 m.
- *Deep zone*: Temperatures in this region are stable throughout the year, depths generally greater than about 8–20 m. Sanner [20] indicates that a gradual increase in temperature beyond these depths can occur due to the Earth's core, on average, 3 °C for each additional 100 m.

Other influences of the subsurface temperature distribution include structural and physical properties, surface cover (e.g. bare ground, lawn, snow), climate interaction (i.e. boundary conditions) determined by ambient air temperature, wind, solar radiation, relative humidity and rainfall [23,40,41]. The natural temperature of the subsurface source is dependent on the Earth's surface climatology, which entails more specifically ambient air temperature, humidity and soil surface characteristics [42]. Furthermore, the subsurface exhibits a thermal lag response with ambient conditions and significantly lower magnitudes of temperature fluctuations with increasing depths.

Rawlings and Sykulski [21] state that for shallow geothermal energy systems to remain effective, it is important to consider the long-term energy balance of the ground. This is not generally an issue if the system provides a balanced heating and cooling with the ground providing equilibrated inter-seasonal storage. However, the natural recovery process, that is the time required to return to the original temperature state, will be delayed when the heat exchanger is installed [43] and the energy use requirements of the system is imbalanced. The recovery process is aided by solar radiation, underground water flow across the site, conduction of heat from the air and the Earth's core, the latter source becoming more significant for depths greater than 100 m below the surface [11,21,22].

If the natural recovery process is not completed due to the large imbalances of heating and cooling needs of the system, the resulting long-term ground temperature can become much higher or lower than natural conditions. If the ground temperature surrounding the geothermal heat exchangers continues to rise throughout the life of the system, heat pump performance can consequently be lowered due to fluid temperature increase [40] and possibly lead to thermal failure of the ground [44]. The significance of thermal failure and its effect on the performance of both the system and structural strength is material specific and dependent on the local site conditions. Long-term temperature increases may also become unnatural and thus harmful to biological life in the ground [18]. Furthermore, heat is increasingly being considered as a form of pollution by certain environmental agencies [22].

The other extreme, significant temperature reductions should also be avoided [21]. Brandl [12] found that, although temperature fluctuations caused by energy foundations have no relevant effect on surrounding soil assuming its temperature remains higher than +2 °C, cooling below this temperature can induce freeze–thaw impacts of the soil. When the temperature is lowered below this, thermal conductivity of the soil's water content or groundwater will continue to decrease slightly until a threshold is reached (freezing), upon which heat transfer rates for the overall media significantly increases because water thermal conductivity rises. A subsequent decrease in heat capacity occurs, reducing system performance.

3.3. Properties of thermal significance

Thermal properties of the foundation material have a significant effect on the performance of the system. This can be problematic for efficient design as these values are complicated and cannot simply be theoretically defined. They are also temperature dependent, which adds to the complexity in their quantification [12]. This highlights the need for detailed knowledge of the site-specific conditions.

Two foundation material properties, which greatly affect the design of the heat pump system, are thermal conductivity (k_s) and thermal diffusivity (α) [21]. Rocks, although harder to reach because they are generally at larger depths, have been found to have significantly higher thermal conductivities and diffusivities [21]. Thermal properties are said to vary according to the properties and proportions of the constituent phases (gaseous, liquid and solid) [37]. Spatial variability and the influence of moisture content and temperature on thermal behaviour have to also be accounted for as soil is often not homogenous. When quantifying these parameters, it is therefore important to consider the degree of saturation of the local soil.

Thermal conductivity is defined as the quantity of heat to flow per a unit time through a unit area of a substance and is strongly influenced by the density of soil and its water content as well as the mineralogical components and chemical properties of pore water [11,12,45]. It can usually be determined to an acceptable level of accuracy using theoretical models or diagrams that consider water content, saturation density and texture of the soil. One such empirical formula is presented by Yari and Javani [9]. For larger scale projects, however, parameter values are best determined through laboratory and/or field testing. Thermal conductivity generally increases with water content as the contact resistance between the ground heat exchangers and the soil is reduced when water replaces air between the soil particles [29]. When heat is extracted from subsoil, there will be migration of moisture by diffusion towards the heat exchanger resulting in an increase of soil thermal conductivity.

Thermal diffusivity quantitatively describes the depth and velocity of penetration of a temperature wave into the ground [12]. An alternative definition offered by Clarke et al. [11] describes thermal diffusivity as a measure of how easily the soil will undergo a temperature change.

Another thermal property that can aid in describing the performance potential of the system is the specific heat capacity of the foundation soils or rock. Brandl [12] defines this as the amount of energy stored in a material per unit mass per unit change in temperature. Dickinson [46] further explains that as thermal energy is stored in both the groundwater and the foundation material, the volumetric heat capacity is a function of the porosity and thermal properties of the respective fluid and solid materials.

3.3.1. Measurement of soil thermal properties

Field or laboratory tests can be used to measure soil thermal conductivity. However, field measurements can be expensive and time consuming. Laboratory measurement techniques can be classified into two main categories namely: steady state methods and unsteady state methods. Thermal conductivity, specific heat capacity and thermal diffusivity of soils can be determined using both methods. The steady state methods measure the thermal conductivity when the temperature of a soil specimen, subjected to temperature gradient, is constant with time at any point and the heat flux through the soil specimen reaches a constant level. This method has been referred to in literature as the divided bar method. The steady state method uses Fourier's heat conduction law to determine soil's thermal conductivity for known heat flux

and thermal gradient. Various techniques are available for the measurement of thermal conductivity under steady state conditions, e.g. guarded-hot-plate apparatus (ASTM C 177-04)[47], heat flow meter apparatus (ASTM C 518-04) [48], guarded-comparative-longitudinal heat flow technique (ASTM E 1225-04) [49], rhometer apparatus [50] and Rapid *k* method [51]. The heat flow meter apparatus (ASTM C 518-04) [48] is widely used because it is simple in concept and applicable to a wide variety of soil types [52,53]. It is a comparative or secondary method of measurement because specimens of known thermal conductivity must be used to calibrate the apparatus. The heat flow meter apparatus consists of two parallel isothermal plate assemblies and one or more heat flux transducers. It establishes steady state one dimensional heat flow through a sample sandwiched between two isothermal plates set at different temperatures.

The unsteady state methods measure soils thermal conductivity during transient states. It determines soil's thermal conductivity while soil's temperature changes due to either heating or cooling. The transient method includes Shannon and Wells [54] method, thermal needle method, ring source method [55] and transient plane source (TPS) technique [56]. The thermal needle method, also referred to as line source method, hot wire method or probe method, is widely used because of its simplicity. It is based on measurement of rate of temperature increase or decrease depending upon heating or cooling along a line heat source within an infinite, homogeneous medium [57–60]. Each method has its own advantages, limitations and assumptions; these are discussed in details in Mitchell and Kao [51], Midttømme and Roaldset [61] and Abuel-Naga et al. [60]. Thermal conductivity of soil has been shown to be a function of mineralogical composition, dry density (porosity), pore fluid, degree of saturation, water content and temperature [52,53,62–66].

3.4. Groundwater

Groundwater flow can have a significant impact on the performance of geothermal heat exchangers potentially complicating the heat transfer process between subsoil and ground heat exchangers. Diao et al. [36] mention the process of water advection in porous medium. This may significantly alter the conductive temperature distribution, as it will result in lower temperature rises and eventually lead to a steady condition.

Rates of groundwater flow can vary significantly based on specific strata types and height of the water table. Diao et al. [36] and Rees et al. [37] both caution that if these ground flows are significant, an adverse effect on the system may result because of potential heat transfer, significant distances away from the structure. This is because heat transfer rates in water are at least 20 times greater than that of air [38]. Many soils commonly exhibit low permeability and thus groundwater flow rates are low and the process of convection in regards to groundwater is minimal [37,38]. This point indicates that groundwater flow is generally beneficial to the thermal performance of the ground heat exchangers since there is a moderating effect on fluid temperatures in both heating and cooling modes. Thermal advection of groundwater is primarily responsible for the inherent benefits, as it alleviates the possible heat build-up around the piles (exchangers) over time. In the presence of static groundwater, incorporating this parameter into design can be achieved through estimates of bulk soil thermal conductivity [37].

A variety of circumstances can lead to changes in groundwater behaviour which may affect the ongoing performance of the system. Examples include precipitation, evaporation, transpiration, vegetation changes, ground works or construction and groundwater abstraction [37]. Brandl [12] also found that the hydraulic, physico-chemical and biological properties of groundwater could significantly vary and should be considered.

3.5. Geothermal heat sources

The type of subsurface heat source that the system taps into can significantly vary the energy potential. The most common heat sources are soil and rock layers upon which the piles are founded. The former is generally more accessible while the latter exhibits significantly more energy potential. The advantages of using rock are balanced by the disadvantage of higher installation costs required to reach the rock strata in most areas. More specific heat sources that are becoming increasingly popular were discussed by Sanner et al. [67] and include spas, thermal springs, tunnels, and mines. The first two choices have been well established as places for bathing and other therapeutic applications. These sources can however be further utilised for heat extraction from used thermal waters and adaptation for heating of surrounding structures.

Tunnels are widely used worldwide and can reach significant depths below the surface. These structures require significant drainage facilities to ensure that groundwater or other surrounding water sources do not infiltrate the structure. The drainage, historically, is extracted through complex pipe systems and subsequently diverted elsewhere, generally nearby rivers or streams. The energy potential of this extracted water is not yet utilised and hence, geothermal energy systems can be installed to extract this energy. This is a technically and economically feasible option as the drainage structure of the tunnel is already included in the design. Feasibility studies in Europe have investigated the use of this type of heat source [67].

An abundant amount of abandoned mines worldwide are being considered for a new purpose, namely a potential heat source. These mines fill up with water due to the recovery of the water table and can potentially act as an artificial aquifer whereby water can be tapped as a heat source for the geothermal energy system. Some systems are already in operation in Germany [67]. As far as the use of energy piles is concerned, some heat sources may provide the opportunity, while others may prefer the use of boreholes or horizontal loops. The choice of system will also depend on type of potential uses in the area.

3.6. Soil type

The soil type surrounding the ground heat exchanger is of paramount importance in terms performance efficiency of the shallow geothermal energy system. Saturated soils will generally conduct heat at a much faster rate than unsaturated material [37]. Loose dry soil traps air and is less effective for heat transfer while damp materials been found to exhibit most desirable heat transfer rates [24]. Soil, which is rich in clay or organic material (shale or coal), has low thermal conductivity and heat will travel slowly through the surrounding subsurface towards the energy piles. In contrast, a high quartz content geology (e.g. sandstone) has high thermal conductivity. The presence of quartz is difficult to accurately determine and may become an issue if present in very high amounts, because an undesirable increase in thermal conductivity will decrease the efficiency of heat transfer interactions with the energy piles [31]. In contrast Florides and Kalogirou [23] found that low-conductive shale or coal layers have higher geothermal gradients than high-conductive sandstone layers and are preferred so it is difficult to determine what the ideal soil type for these systems is.

4. Design considerations

The following section will look at existing design standards for energy piles, the tools for prediction of system performance and present an appropriate design procedure along with current implementation issues to be aware of.

4.1. Current design standards

The *German VDI 4640* design standard [68–71] is the most comprehensive standard to date comprising of four sections published from 2000 to 2004. Section 2 in particular deals with ground-coupled heat exchangers, which include energy piles. Other guidelines include the *IGSHPA guidelines*, which are used by some contractors in both the United States and the UK [72] and the *guidelines for geoexchange systems in British Columbia*, Canada [73,74].

4.2. Performance assessment

Three methods allowing for performance assessment of ground-source heat pump systems during the design stage and after construction include:

- The coefficient of performance (COP)
- Mathematical modelling
- On-site testing

In the context of ground-source heat pumps, traditionally the most important performance assessment quantity is the coefficient of performance (COP), which is defined by Eq. (1). The COP indicates how much heat can be gained for a unit input of electrical energy. Design often aims for values between 2 and 4, although Tarnawski et al. [18] regards closed-loop systems to generally offer COPs between 3 and 5.

$$\mathrm{COP} = \frac{\text{Heat output [kW]}}{\text{Electrical input [kW]}} \tag{1}$$

Each individual component of the system has an effect on the overall COP value and thus optimizing the design of each individual component can ensure an appropriate COP. Selection of the heat pump has a significant impact on overall system efficiency and consequentially the COP [9,28,29]. In operation stage, environmental factors can also affect the system performance. Michopoulos et al. [39] for example explain that injecting heat into an already high temperature ground will make the system inefficient resulting in a lower COP.

The mathematics of ground-source heat pumps are based on cylindrical heat source theory [40,75–77]. Heat transfer along the exchanger is described as radial and relatively constant. Many known models are based on this particular theory, one example of which is TRNSYS [40]. Energy–exergy analysis is another common tool used to model performance of various systems. An extensive overview is given by Ozgener [78] and Ozgener and Hepbasli [33]. A field application of exergy analysis has been carried out in China by Gao [7]. Tarnawski et al. [18] applied energy analysis, which considers the various components of energy consumption in an energy balance equation, to three years worth of monitoring data in Japan. Energy analysis is taken into consideration by the computer software package called Ground Heat Exchanger Analysis, Design and Simulation (GHEADS), which provides outputs of daily average COP, energy consumption, ground temperature distributions and volumetric soil moisture near the heat exchanger in return for meteorological data, house heating and cooling load data inputs [18]. This is not the first model of its kind as a report by the same author more than a decade previously, looking at a model that couples surface and subsurface climatology with ground-source heat exchanger operation [79]. It is however still of great importance and interest that existing models are refined or coupled with other algorithms to obtain better accuracy. Modelling these systems is still at a young stage. Current research looks into the development of accurate thermo-hydro-mechanical models for different soil media [77,80,81].

In order to assess the performance of the system once in operation, various tests are available. The thermal response test is probably the most popular choice and although a lack of literature documenting this test on energy piles has been found and the majority of reports have involved testing on borehole heat exchangers [17,23], use of the methodology can be easily transferred across different heat exchanger systems. The test involves applying a specific thermal load into the ground-source heat exchanger and measuring the resulting temperature changes of the circulating fluids. The results include graphs of fluid temperature development against time, thermal conductivity and thermal resistance of the exchanger, which provides the temperature drop between natural ground and fluid in pipes. For the assessment of thermo-hydro-mechanical behaviour of the subsurface, the 'isothermal test' can be suggested. It has however yet to be extensively used on energy piles as current research primarily uses this test for the assessment of impact on deep geological repositories [81].

4.3. Design steps

Many important factors that need to be considered in the design of geothermal energy pile systems have been identified in past applications [5,19,20]. While rules of thumb exist in design, their use for larger scale systems is not recommended [22]. In the context of providing an alternative energy source, a general design procedure can be developed. Each of the following steps requires careful consideration of the pertinent aspects covered.

Knowledge of the desired heating and cooling characteristics of the building [20] is probably the most important first step to be taken. Occupancy is another important aspect at this stage [5]. These details determine whether a monodirectional (one operation mode only) or bidirectional (dual-operation mode) system is needed, what the preferred soil properties are for optimum performance, and whether any design is capable of providing the necessary energy requirements without additional assistance.

As with conventional pile design, the assessment of the systems requirements should then be followed up by an extensive geotechnical site investigation [5,6,14,82] including (but not limited to) the following details:

- Geological strata (e.g. shallow profile as well as identification and depth of the foundation rock.)
- Geotechnical properties (e.g. water content, density, void ratio, hydraulic properties, strength parameters, etc.)
- Geothermal properties (e.g. thermal conductivity, specific heat capacity at different temperatures, in situ ground temperatures, the existence of thermal gradients, etc.)
- Hydrogeological properties (e.g. depth to groundwater, fluctuations of water levels, flow direction and velocities, etc.)
- Mineralogical and geochemical soil properties

The more information available, the more efficient the design can be thus achieving the most optimum performance and output of the system. Some of the above investigations may already be required if the geothermal energy piles have the existing primary purpose of structural stability. Pile dimensions and spacing dictate land and excavation requirements as well as system performance, but are in turn strongly influenced by several factors including: quantity of piles required to satisfy both structural and thermal loads, project budget and pile depths if limited by site geology [14,19].

Absorber pipe material should be of thermally fused HDPE, which provides strength and reliability. Nowadays, special fittings are available for ground-source heat pumps [6]. The size and number of pipes as well as shape of the embedded loop will affect

installation and pumping costs as well as influence pipe friction loss and achievable flow rates [7,19].

The choice of heat transfer fluid used is also important and Kavanaugh [6] recommends the use of less antifreeze fluid (unless the situation calls for it). Choice of fluid should be based on availability, economics and non-corrosive properties [19]. An adequate flow rate of the fluid through the system should also be selected. It has been established that low flow rates are preferred to allow for better delivery of heating and cooling requirements [9,19].

Additionally, it should be stressed that operation of the system should be user-friendly to allow easy operation by building occupants [6]. Upon completion of the initial design, implementation becomes the next issue.

Engineers should ensure that all details have been obtained in order to produce the most effective design. It is not sufficient to adopt one system for many applications as consideration has not been given to the environment being dealt with. It has been found that owners of these systems however remain satisfied due to the inherent benefits offered, but interaction between all involved parties is paramount for proper implementation of the technology [32].

4.4. Implementation issues

In theory, geothermal energy pile foundations can work efficiently if properly designed. In practice, the performance of these systems is dependent on a lot more issues such as installation, component defects and proper use. Being relatively new, no definitive procedure exists for construction of these systems and this is an important factor that needs to be addressed as many stories exist of flooded construction sites, failed drilling jobs, and poorly performed systems [22]. Amongst the design suggestions listed by Kavanaugh [6] it is important that experienced contractors in this field are consulted if problems are to be minimized. The issue of apparent skills shortages is currently being addressed in the UK by the Ground Source Heat Pump Association (GSHPA) [22].

5. Applications and experiences around the world

Ground-source heat exchangers have been found to have a range of applications in providing geothermal energy. This section will highlight the areas where energy piles are a feasible choice and present several case studies in countries, which have had decades of experiences with this technology such as Austria, Switzerland and Germany. Examples from countries, which are introducing this technology and currently conducting research to learn about any potential problems that may arise, are also featured.

5.1. Different applications of ground-source heat pump systems

The most common use of this technology revolves around domestic and commercial space heating and cooling as well as the production of hot water [21,83]. Rawlings and Sykulski [21] list a number of commercial facilities, where these systems can be found including offices, schools, shops, hotels, sports centres, institutional buildings and military complexes. Adding to the list are other elements of infrastructure such as tunnels [13], green houses, roads, bridges [22] and the agriculture industry [18].

Energy piles are suited for buildings that already require structural foundation piles. For tunnels and other structures, their use becomes less feasible, on an economic and practical level. Consequently, the choice of horizontal loops and diaphragm walls are attractive alternatives. Outfitting road tunnels and underground subway tunnels in urban areas can allow for profitable heat extraction [13] as larger ground volumes are activated allowing for greater amounts of heat extraction and storage. Suggestions have also been made to use carparks as large collectors to supply nearby buildings for their heating and cooling needs [22].

The potential for this technology for the agriculture industry has been assessed by Tarnawski et al. [18] and Ozgener and Hepbasli [33]. Heating and cooling demands for growing vegetables in greenhouses, drying crops, heating water at fish farms and pasteurizing milk have all been considered. The farming sector has also been regarded to have fewer restrictions on ground availability [18].

5.2. Improving the thermal imbalance in cooler countries

It has been found that solar panels aid in improving the thermal imbalance when heating is the predominant operation of the system [12]. The idea of coupling the two renewable energy technologies was suggested in the 1980s and has become an interest in China [40,42,43,84]. The underlying concept is to utilise solar collectors to assist in recharging the ground with thermal energy during the summer months and to fulfil part of the required heating demand in winter. According to Zogou and Stamatelos [84], this technology has shown its effectiveness in Northern Europe and is now under research in Asia.

General operation procedures would involve the collectors operating mostly throughout summer in an effort to recharge the ground and during the daytime in winter to supply the heating requirements. There are a few issues to be aware of when incorporating a solar collector into the system. Studies by Bi et al. [42,43] showed that care must be taken in the design as the collector's COP has an effect on that of the overall system. Quoted values of COP showed the combined system was slightly less efficient (2.78) than the ground-source heat pump by itself (2.83). Ozgener and Hepbasli [33] had similar results with a COP of 2.64 for the ground-source heat pump system and a decreased value of 2.38 for the combined system. Several design aspects were also highlighted as important such as the fluid temperatures entering the collector, which affect the efficiency of energy collection. Despite the observed decrease in efficiency, there is still interest in this combination for three main reasons: the reduction in fossil fuel consumption, the use of non-polluting sources of energy and long-term environmental sustainability [12,33]. There is a particular focus on the environmental benefits as the ground is used as a substitute to batteries, which currently are the common form of storing solar energy.

5.3. Improving the thermal imbalance in warmer countries

In the situation where cooling is the predominant operation of the system, the ground can be used as a cold storage to offset the otherwise long-term rise in ground temperature. Fan et al. [85] investigated this possible solution for systems installed in certain regions of China that lie in the middle and downstream of the Changjiang River. These regions exhibited warm climate conditions and as a result, the systems were required to output significantly higher cooling loads compared to heating loads. Due to the imbalance of the energy requirements, the soil temperature gradually began to increase over time due to the inability to complete the recovery process. This rise in temperature resultantly decreased the performance of the overall system. In order to solve this problem, a new system, referred to as the integrated soil cold storage and ground-source heat pump system, was implemented.

In order to reduce the imbalance caused by the significant cooling requirements of buildings, this system, charges cold energy to the soil at night in order to aid the system in producing chilled water to meet cooling needs during daytime. By injection cool night temperatures into the soil, the soil will exhibit lower temperatures during the day and hence its performance will

significantly improve when required to provide cooling within the building. There is also the economic advantage of using the system at night because this is during the energy usage off-peak period and will result in a decrease in power consumption during the day since the system will perform more efficiently.

5.4. Other innovative studies on ground-source heat exchangers

Two innovative ideas mentioned in the covered literature included the use of CO_2 as a heat transfer medium and the treatment of urban stormwater runoff [86,87]. The use of liquid CO_2 as a heat transfer medium was investigated by Ochsner [86] and several advantages found this innovation promising including smaller space requirements for CO_2 pipes, low operation costs, environmental friendliness and more efficient heat extraction from surrounding soil. Scholz and Grabowiecki [87] proposed a novel idea of using the technology to treat urban runoff. If successfully developed, the attractiveness of the technology should further increase, especially in the Australian environment, where there is a drive towards stormwater treatment and reuse. These innovations are still subject for future research, but nevertheless highlight the potential that these systems have.

5.5. Experiences in Austria, Switzerland and Germany

Austria, Switzerland and Germany can be regarded as the pioneering countries that have investigated this technology for decades. Extensive use of ground-source heat exchangers has been featured in Austria. Two notable examples are lot LT24 of the Lainzer tunnel and Uniqa Tower in the centre of Vienna. Both of these have received attention from several authors [12,13]. The section of the Lainzer tunnel (currently under construction) employs the use of energy piles in its side walls. Of the numerous bored piles installed, every third pile is converted into an energy pile to extract geothermal energy for heating and cooling of railway stations, other administrative buildings and prevention of frost damage to platforms and bridges. Uniqa tower is founded on a raft foundation with two diaphragm walls reaching to depths of 35 m. Energy is extracted for space heating within the building and, as an aid to conventional systems, to satisfy cooling loads [13].

Switzerland has had several decades of experience with ground-source heat pumps. The technology is used in many residential houses in the form of borehole heat extractors for heat distribution. The largest borehole heat extraction system is located at a spa near St. Moritz and consists of 40 bores [67]. Two notable examples of projects, which have employed the use of energy piles are at the Swiss Federal Institute of Technology in Lausanne and Dock Midfield Airport. The Lausanne project in particular has also been part of an extensive performance monitoring program, in particular the investigation of the thermo-hydro-mechanical behaviour of surrounding soil [22,80]. Conclusions drawn from the investigations reported by Laloui et al. [80] showed that thermo-elastic strains were more pronounced than mechanically induced strains. Effects were observed 1 m away from the pile shaft. The overall effects of thermal loading on the pore pressures and effective stresses were however regarded as minimal. Axial stresses were a greater concern at the pile toe than stresses induced by the building's dead weight. Friction resistance appeared to not be affected by temperature [80]. Of the 440 foundation piles at Dock Midfield airport, 300 were converted into energy piles for heating and cooling purposes [80,88]. Performance assessment concluded that 85% of the annual heating demand (approximately 2700 MWh/year) was supplied by the heat pump while a combination of energy piles and conventional cooling systems were able to meet annual cooling demands (approximately 1200 MWh/year).

In Germany, the oldest seasonal thermal energy storage system, which was built in 1998 is located in Neckarsulm consisting of 696 boreholes [22]. Energy piles have been used in some commercial projects such as the 200 m high Frankfurt Main tower. This building is founded on a 30 m $\times$ 50 m base supported by 213 piles, 112 of which are energy piles of 30 m in length [80,89]. Berlin's International Solar Center employs 200 energy piles to meet 20% of heating and 100% of cooling demands through seasonal heat storage [90]. The country has been quite receptive towards this new technology with the federal government offering incentives in an effort to promote the ground-source heat pump market. It has however been recommended that for this alternative energy source to be economically viable, both heating and cooling operations should be considered [67].

5.6. Experiences in the UK

Energy piles are a relatively new technology in the UK and are undergoing extensive research. Projects of particular interest are Keble College, Oxford University and the test site at Lambeth College. The first energy pile project in the UK began in 2001 using Austrian technology at Keble College, Oxford University [12]. Both standard foundation piles and secant piles for retaining walls were outfitted with absorber pipes. Significant benefits were experienced including those mentioned in Section 5.5. The system has been running without problems since its inception [12].

Lambeth College's new sixth form centre is undergoing final touches to construction. A total of 146 energy piles at 25 m depth were installed for heating and cooling and for the reduction of carbon emissions [22]. Bourne-Webb et al. [77] conducted an investigation on the impact of heating and cooling processes on the geotechnical performance of the pile, a study regarded as the first of its kind in the UK. Results showed that it was highly unlikely for thermal behaviour to impact the geotechnical capacity of the pile, however potential issues with concrete stresses were mentioned requiring incorporation of thermal effects during pile design to prevent requirements imposed by design codes from being breached [77].

5.7. Other relevant countries

The United States of America has in place some large geothermal energy pile systems. Stockton College is an example of one of a structure that utilises this system. When built in the early 1990s, it was considered as the largest single seasonal underground thermal energy facility in the world. This system utilised a large amount of heat exchanger wells and a water source heat pump unit to serve the heating and cooling of the College campus. The implementation of this system resulted in a reduction of 25% in electricity and 70% in natural gas consumption. Overall the system was found to significantly contribute to a confirmed 13% overall reduction in CO_2 emissions at the College [91,92].

Countries such as the Netherlands, Belgium, France, Poland, Sweden, Norway, Canada and Iran and several others have all employed the use of ground-source heat pump technology, however progress has yet to be seen in the use of energy piles [9,93].

6. Benefits and limitations of the technology

The implementation of geothermal energy systems has economic, environmental and social benefits and these benefits are becoming more significant with large advances in the development and design of these systems over time.

Recent advances in the development of ground-source heat pumps have resulted in an economically viable tool to capitalize on

the geothermal energy present in the ground [13]. The construction costs of these systems remain the critical costs to ensure economical competitiveness [36]. The risk of over design can significantly increase initial costs of the system [6]. Historically, high installation costs have often prevented actual implementation, but incorporating these systems with structural piles has significantly improved this economic issue. A comparison of geothermal heat pump systems that utilise energy piles and conventional borehole geothermal heat pump systems was undertaken and it was found that the former system is capable of providing a larger capacity at a lower initial cost [94]. The initial installation costs are also generally counteracted by low operating and utility costs [13,27,83,95,96].

Geothermal energy systems have been found to provide substantial long-term cost savings in relation to conventional systems and with an investment-return period of 5–10 years depending on ground strata, subsurface properties, and alternative energy prices [14,97]. The latter was confirmed with investigations in Turkey that found that ground-source heat pumps offer economic advantages over all conventional heating methods (electrical resistance, fuel oil, liquid petrol gas, coal, oil) except natural gas. The main reason for this was due to the abundance of gas available in Turkey [98].

The main environmental benefits are the reductions of fossil energy consumption and the use of a clean, self-renewable energy source [13,14,27]. This is becoming more significant as there is a growing concern over global warming due to CO_2 emissions from the use of fossil fuels. The utilisation of shallow geothermal energy will aid in climate protection, which subsequently assists in fulfilling international obligations and emission reduction targets (e.g. Kyoto Protocol).

The efficiency of these systems is inherently higher than that of air-source heat pumps because the ground maintains a relatively stable source/sink temperature, allowing the system to operate close to its optimal design point throughout the year, allowing achievement of a higher COP [28,29,36,95,99]. Boennec [22] indicates that these systems have the potential to offer up to 80% overall carbon reductions. Kikuchi et al. [96] report that ground-source heat pumps use 20–40% less energy for heating and 30–50% for cooling.

There are also benefits in regards to the design of the system. This technology can be adopted in nearly all ground conditions and is not limited to urban areas. Further benefits mentioned by Rawlings and Sykulski [21] include low noise due to the absence of external fans, no roof penetrations, high security because an external unit does not exist and increased safety due to the absence of explosive gases are within the building. Investigations undertaken on existing systems found that the owners presented further benefits such as financial incentives in the form of design cost offset and capital grants, less space requirements, preservation of the aesthetic appearance on-site, no exposure to weathering, lower energy consumption to operate and remotely available [28,29,32].

Like any other energy systems, especially new technology, limitations and consequently customer uncertainty do exist. Brandl [14] mentions that reduced efficiency of the heat pumps and absorber systems will occur when substantial temperature fluctuations take place during the year. If the soil at the site consists mainly of dry sand or gravel, deeper piles and a larger area of absorbers are required which may significantly increase costs and reduce economic benefits offered by such systems. Another limitation is the corresponding installation cost with pile length, but this can be offset due to the increase in energy potential with depth [14].

If the systems are installed in climates that may result in soil freezing, antifreeze solution is required, which may induce potential for leaks. This can however be avoided with the correct use of fluid within the system. Another issue that may be problematic for some systems and is likely to result in heavier regulations is the need for balance in regards to rejection and extraction of heat. This balance is necessary to ensure long-term performance and prevention of short-circuiting of individual systems and impacts on nearby installations [46].

With this system still relatively new, investigations have shown that improper setup, misuse and designs have been found to occur resulting in inadequate flow rates, leaks within the system, inadequate heat exchange with the ground and interference amongst components [32]. These issues are however likely to become less of a concern over time through experience, better design and training.

In terms of design, the major limitation that exists is that no theoretical model used to predict performance is able to consider all the parameters that affect the system. Specifically, most models do not account for the various soil and rock conditions as they cannot sufficiently represent complicated geological strata [99].

7. Future prospects and feasibility in Australia

As a hot and dry country, climate change poses a substantial threat to Australia's economy and the way of life. For the past twelve years, Australia has experienced eleven of the hottest years since records began and temperatures are projected to continue to rise over the next century. Global and local communities need to focus on reducing greenhouse gases, because even though the effects of global warming can no longer be avoided, people can make efforts to help minimize it.

7.1. Benefits of utilising geothermal energy pile foundations in Australia

Although there are a significant amount of advantages to implementing geothermal energy piles, the environmental benefits are likely to be considered the most attractive. The Australian Government had recognised the potential impacts of climate change and have put in place certain legislation and policies focused on reducing carbon pollution. The White Paper [2] specifies goals to cut carbon emissions, by the year 2050, to 60% of the levels emitted in 2000. Furthermore, by the year 2020, the Australian government has committed this country to reduce its carbon pollution by up to 15% below 2000 levels via the Kyoto Protocol.

Geothermal energy pile foundations are one solution that has great potential in helping Australia to reduce carbon emissions and meet this commitment. This is confirmed as the Energy Efficiency Action plan states that energy use in households for the purpose of heating and cooling during the year 2005 contributed, on average, to 26% of the total greenhouse gas emissions in Australia. Governments, such as the state of Victoria, already have in place specific goals to implement alternative energy sources, the Victorian Environmental Sustainability Framework (2005) states that the Victorian Government aims to increase the share of Victoria's electricity consumption from renewable energy source from the 4% (in the year 2005) to 19% by the year 2010 [100]. Furthermore, they have recognised geothermal energy as a viable option and have in place a Geothermal Energy Source Act (2005), which states the specific requirements for exploration permits, retention leases and extraction licences.

The inclusion of piles for structural integrity is already commonly identified in many commercial and industrial buildings in Australia. One example of an area where piles are commonly used because of foundation limitations is Melbourne where Coode Island Silt is found along the urban area of Southbank. As a result,

the adaptation of structural piles to include the geothermal energy pile systems is a very feasible and economically viable option.

The Australian continent is extremely large when compared to most other countries. Majority of the land utilised in Australia is along the coast, with various remote towns such as Aires Rock in the centre. These remote towns and farms can benefit from geothermal energy systems by exploiting the advantage of the system's self-sufficiency and decentralised character.

7.2. The Australian environment

The main cities in Australia exhibit significantly different types of foundations. Some predominant features of the large cities across Australia include large aquifers that could be tapped into such as the Ipswich Basin in Brisbane, Swan Coastal Plain in Western Australia and the Great Artesian Basin that covers significant areas of Queensland, New South Wales and Victoria. These aquifers have previously been tapped into for domestic, commercial and irrigation water supply but are no longer encouraged due toman-made salinity issues. Tapping into these aquifers rather than conventional soil and rock for extraction of shallow geothermal energy is a promising alternative.

Some cities are predominantly founded on sandstones such as Hallett Cove sandstone in Adelaide and Hawkesbury sandstone in Sydney. This may result in increased costs of implementing geothermal energy pile foundations as dry sand or gravel makes deeper piles and larger area of absorbers necessary [14].

The area of Melbourne is of particular focus due to the already large use of piles for structural purposes. Based on geological maps from the Victorian Geological Survey, the outer Eastern to North-Eastern areas of Melbourne consist mainly of mudstone, sandstone and siltstone whereas is the outer Northern and Western areas the geology consists predominantly of new volcanic materials such as basalt and scoria. Closer to Melbourne itself, the foundations consist of a variety of clay, silt, sand, gravel and peat [101]. The main implications of this geological information are that each of these types of soils will affect the performance of the systems differently due to the varying thermal conductivities and geothermal gradients. This information also illustrates the need for detailed geotechnical investigations to be carried out in order to accurately determine the subsurface that will be in contact with the ground heat exchangers.

7.3. Research challenges

An issue that may arise with implementing this system in Australia is the imbalance between the heating and cooling needs of the user and needs to be explored further. As a result of the warm climate conditions within Australia, there is likely to be more demand for cooling or otherwise known as heat rejection into the ground. The importance of achieving a balance between heat rejection and extraction has resulted in the requirement for building occupants to inform environmental authorities each year of the respective volume of energy abstraction and rejection. This ensures that individual systems do not short-circuit, that the natural recovery process can still occur long term and prevents possible impacts on other nearby installations [46]. The thermal imbalance has been identified as a problem for some systems in other countries with similar climate conditions and a solution has already been discussed in Section 5.3 [85].

Currently, a large research programme is being carried out at Monash University, Australia on geothermal energy piles. The research programme consists of detailed laboratory investigations and field study of geothermal pile foundations. The laboratory study investigates the impact of heating and cooling on surrounding soil at small scale. The geothermal pile at laboratory scale is being imitated by a temperature-controlled heater. The field study includes static load test of a fully instrumented large-scale pile connected to a heat pump. The field study aims at measuring stress, deformation, temperature and thermal properties of the fully instrumented geothermal pile and surrounding soils. The study at Monash will present a case whether geothermal energy piles are a viable solution for heating and cooling of structures in Australia.

8. Conclusion

This review covered an extensive collection of literature, looking at the design, environmental impacts and operation experiences of geothermal energy pile systems. Developments in this technology have resulted in systems that are cost efficient, environmentally beneficial and socially acceptable. Furthermore, geothermal energy pile systems have been found to have great potential as an aid in tackling climate challenges and meeting legislation requirements. Research has found that over 80 countries have utilised shallow geothermal energy technology and the benefits and opportunities gained from these experiences can be adapted and applied to the Australian environment. Potential challenges of long-term effects on ground temperatures and other environmental impacts have to however be addressed before further progress can be made.

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